AD-A270 848

93 10 15 161

93-24617

...NTATION PAGE

Form Approved
OMB No. 0704-0188

...ted to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, ...eviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this ...urden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson ...ffice of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

	...RT DATE Aug 93	3. REPORT TYPE AND DATES COVERED Technical

4. TITLE AND SUBTITLE
MOCVD-~~Grown~~ InGaAsP Double Heterostructure Diode Lasers

5. FUNDING NUMBERS
2
DAAH04-93-G-0044

6. AUTHOR(S)
M. Razeghi, et. al.

DTIC
ELECTE
OCT 2 0 1993
S A D

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Northwestern University
Center for Quantum Devices
633 Clark Street
Evanston, IL 60208

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 31108.1-PH

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
InGaAsP/InGaP/GaAs compound has been recently proposed to replace AlGaAs/GaAs as advantageous material for high-power laser applications. In this work we report successful fabrication and study of broad-area double-heterostructure InGaAsP/InGaP laser diodes reproducibly grown by MOCVD. The diodes demonstrated near-100% efficiency of spontaneous radiative recombination in the active region. Threshold current densities of 700A/cm^2 obtained for 900um-long cavities were close to the theoretically predicted low limit and lower than respective values experimentally obtained for similar AlGaAs/GaAs diodes. Narrow far-field distribution with FWHM of 28^o in the direction transverse to p-n junction plane may be of practical interest. Saturation of spontaneous emission above the threshold as well as a flat near field pattern confirm the uniformity of lasing intensity across a 100um-wide stripe and the homogeneity of the structures studied. Relatively high internal losses of approximately 40cm^{-1} and low differential quantum efficiency of 25% were shown to be inherent for this laser structure design and should be overcome by a combination of the advantages of separate-confinement heterostructures with this laser-quality material.

14. SUBJECT TERMS
GaInAsP-GaAs, High-Power Laser, Heterostructure

15. NUMBER OF PAGES
18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Principal Investigator: Prof. M. Razeghi

Material growth and characterization:	Staff	Students
	Dr. E. Kolev	X. He
	J. Gwilliam	J. Hoff
		C. Jelen
		S. Slivken

Laser processing and measurements:	Staff	Students
	Dr. D. Garbuzov	J. Diaz
	Dr. L. Wang	I. Eliashevich
	Dr. W. Carvalho	K. Mobarhan

Theoretical calculations: X. He
H.-J. Yi

MOCVD-grown InGaAsP double heterostructure diode lasers

Center for Quantum Devices, Department of Electrical Engineering and Computer Science, Northwestern University, Evanston, Illinois 60208

In the previous works [1-4] where MOCVD technology was used, it has been demonstrated that aluminum-free InGaP/GaAs system has many advantages in comparison with conventional AlGaAs/GaAs system for the optoelectronic device fabrication including strained 0.98μm laser diodes [5-6]. However, till now, Al-free InGaAsP/GaAs 0.8μm lasers that are of great practical importance, have been prepared only with liquid phase epitaxy method [7-8] which does not provide the possibility for full realization of all advantages of Al-free system for high power laser diode fabrication as well as for development of their mass production capability. In this report we demonstrate the first MOCVD grown InGaAsP/InGaP/GaAs laser emitting near 0.8μm.

The simplest version of a laser structure that is a double heterostructure was prepared and investigated in these first experiments. The band diagram is schematically shown in Fig. 1. InGaP/InGaAsP/InGaP epitaxial layers were grown on (100) oriented Si-doped GaAs substrates with doping concentration of $1\times10^{18}cm^{-3}$. The laser structure consists of (i) 0.7μm Si-doped InGaP (N_d=$4.7X10^{17}cm^{-3}$) as the confinement and cladding layer; (ii) 0.1μm undoped InGaAsP active layer with background doping concentration lower than $10^{17}cm^{-3}$; (iii) 1.5μm InGa? Zn doped (N_a=$5.6X10^{17}cm^{-3}$) as the second confinement and cladding layer; (iv) 0.1μm GaAs contact layer (N_a=$1X10^{19}cm^{-3}$). The distribution of impurity concentration obtained by electrochemical capacitance-voltage profiling across the structure is shown in Fig. 2. The details of the growth and material characterization are presented elsewhere [9].

Though broad-area lasers are of small practical importance because of high threshold currents, the data obtained for them are often used as reference values or for the purpose of comparison. The investigated broad area contact laser diodes with stripe width of 100 and 200μm were fabricated of two wafers (#36 and #43). 100μm - wide stripe diodes were manufactured of both structures at the Center for Quantum Devices. For comparison, 200μm - wide stripe lasers with Ti/Pt/Au p-contact were made of wafer #43 by Amoco Technology Co. 100μm stripe lasers had annealed Au/AuZn/Au p-contact, metallization and p-GaAs between the stripes had been removed, thus providing an opportunity to observe spontaneous emission through p-InGaP cladding layer in the direction normal to the stripe. Both types of diodes had AuGe/Ni/Au n-contact. Diode chips with cavity length varying from 110 to 910 μm were cleaved and tested with needle probe under pulse operation. Several 100μm and 200μm - wide stripe diodes were In-bonded on copper heatsinks.

Fig. 3 shows I-V characteristics for two bonded diodes with stripe widths 100 and 200μm having the same contact area $\sim 10^{-3} cm^2$. As can be seen, the characteristics shown are very close to each other, cutoff voltage exceeding E_g of the active region by 0.4-0.5 V. Since this feature was observed for the diodes processed independently in two different ways, we suppose it to be attributed to the intrinsic properties of the laser structure rather than to the fabrication procedure. For both types of diodes series resistance decreases at higher current densities and at J over $1 kA/cm^2$ is close to 1 Ohm. This value is several times higher than that for the best AlGaAs diodes and calculation shows that a substantial part of this resistance is introduced by p-InGaP cladding layer and may be eliminated with higher doping of this layer.

Spectra of lasing for two diodes with cavity length of 500μm prepared from wafers #36 and #43 are given in Fig. 4. The close lasing peak positions for the diodes fabricated in different growth runs imply a good reproducibility of the technology developed.

The threshold condition for lasing to occur is that gain should be high enough to compensate for all losses through the length of the cavity during one period of oscillation. A pumping current necessary to provide this value of gain is the threshold current. It is

convenient to describe the quality of planar laser structure in terms of threshold current density rather than absolute threshold current. Having a laser stripe long and broad enough to neglect all mirror and lateral effects, threshold current per unit area depends exclusively on specific quality of the wafer. Minimal threshold current density is highly desirable. It results in low Joule heating of laser device and therefore is important for high-power applications. Threshold current density depends on various laser structure and material parameters (d-active layer thickness, η_i-internal quantum efficiency, J_o-transparency current density, Γ-optical confinement factor, β-fitting parameter, α_i-internal losses, L-cavity length, R-reflectivity of the laser mirrors) and is given by:

$$J_{th}=d/\eta_i\,(J_o+1/\Gamma\beta(\alpha_i+(1/L)\ln(1/R))) \quad (1)$$

Physical meaning of those parameters will be discussed later.

A linear gain-current relation is assumed here:

$$g_{material}=\beta(J-J_o) \quad (1a)$$

Fig. 5 shows the threshold current density versus reciprocal cavity length for 100μm - wide diodes* fabricated of the structures #36 and 43. The results obtained for the bonded diodes are shown in the same graph. No substantial difference in J_{th} was observed for bonded and unbonded diodes with cavity lengths shorter than 500 μm. However, for the chips longer than 500 μm, bonded diodes exhibited lower threshold current densities than under testing needle. Minimal values of threshold current densities obtained are 700-800A/cm^2, that is better than for similar InGaAsP/GaAs double heterostructure lasers grown by liquid phase epitaxy [10]. Those results are also superior than well-known data of 1kA/cm^2 for AlGaAs diodes with the same bandgap difference between active region and cladding layers and with a similar width of the active region (d~0.1μm) [11]. The quoted data for AlGaAs are close to theoretical predictions [12]. We also calculated threshold currents for long-cavity lasers, assuming refractive index and its dispersion for InGaAsP and InGaP corresponding to the known values for AlGaAs compounds with the same bandgap [13]. For double heterostructure, which is essentially a three-layer waveguide, optical confinement

* 200μm - stripe laser diodes demonstrated the same J_{th}.

factor Γ is roughly proportional to d^2 for $d < 500Å$. Generally, Γ may be calculated as

$$\Gamma = \frac{\int_0^{d/2} \cos^2(\kappa x)\,dx}{\int_0^{d/2} \cos^2(\kappa x)\,dx + \int_{d/2}^{\infty} \cos^2(\kappa d/2) \exp[-2\gamma(x - d/2)]\,dx} \quad (2).$$

In our case Γ for d~0.1µm was determined to be about 0.3. Utilizing this value of Γ it was previously showed that for the diodes with cavity length ~1mm the value of I_{th} = 700 A/cm^2 is close to the minimal values of threshold corresponding to the 100% internal efficiency of radiative recombination of carriers in the active region[10]. η_i is the internal quantum efficiency given by the ratio of radiative recombination rate in the active region to the total recombination rate. This important parameter is the number of photons emitted in the active medium per one electron injected.

Additional confirmations of the assumption of η_i~100% were given by our studies of external efficiency of spontaneous emission. This parameter integrates radiative recombination efficiency with losses in laser structure giving a number of photons emitted per injected electron. It can be measured experimentally as

$\eta_e = eP_{out} / h\nu I$. ....(3)

and is linearly related to η_i as

$\eta_e = \gamma\eta_i$ ....(3a),

where γ is current-independent coupling factor depending upon the geometry and absorption losses.

Spontaneous emission intensity observed in the direction normal to the stripe increased linearly with current up to the value of about 1kA/cm^2 and demonstrated a weak temperature dependence (a decrease of no more than 25% for the temperature increase from 300 to 380K at 400 A/cm^2), as shown in Fig.6. Both of those facts indicate that major part of the injected carriers recombine radiatively in the active region. However, those experiments did not provide for estimating the absolute values of external efficiency,

since major part of the radiation emitted towards the surface was absorbed by stripe contact metallization. In order to determine the external efficiency, we fabricated and bonded very short diodes with cavity length of about 100 μm. The current dependence of the intensity of spontaneous emission observed in continuous wave operation through the mirror of one of those short diodes is shown in Fig.7. External quantum efficiency, determined according to eq. (3) from the linear part of this curve, where effects of heating are negligible, is ~0.4%. This value seems quite consistent with $\eta_i \sim 100\%$, since our estimates show the maximum value of η_e for the radiation propagating through a non-absorbing waveguide to the mirror cannot exceed 1.5%. This value was previously obtained for short cavity SCH-SQW LPE-grown InGaAsP/GaAs laser diodes. In our case only long-wavelength part of spontaneous emission can be efficiently coupled out through the mirror even for the diodes with L~100μm due to a strong self-absorption inside of their 0.1μm - thick active layer and $\eta_e \sim 0.4\%$ indicates a very high value of η_i.

A value of T_0 is used to characterize the threshold current behavior under changing lattice temperature. With temperature growing current leakage over the barriers and nonradiative recombination rate are likely to increase, resulting in higher values of threshold current. This dependence is observed in the form of experimental relationship:

$$I(T) = I_0 e^{T-T_0/T_0} \qquad (4)$$

Fig.8 shows temperature dependence of threshold current for a sample with L = 710μm with $T_0 \sim 90^0C$. This value is somewhat smaller than that typical of AlGaAs lasers with higher barriers and consequently better carrier confinement.

Fig.9 presents a far-field pattern in the direction transverse to the plane of p-n junction for one of the 200μm - wide diodes. A relatively small half-width of the angular distribution ($\sim 28^0$) exactly corresponds to the calculated value of $\Gamma = 0.3$ which we used for threshold current calculations. Narrow far-field distribution is of practical interest since high laser beam divergence may prevent efficient coupling of emission into optical fiber. At the same time deep penetration of lasing mode to the cladding layers may have a negative effect on some other parameters of the laser diodes. For

example, in these first experiments we were not able to obtain high differential efficiencies typical for contemporary lasers with quantum well active regions. Differential quantum efficiency is a fraction of electrons that is converted into light output if injected by increasing the driving current:

$$\eta_d = e\Delta P_{out} / h\nu\Delta I \qquad (5).$$

At threshold η_d is related to the internal quantum efficiency of stimulated emission as

$$1/\eta_d = (1/\eta_i)(1 + \alpha_i L/\ln(1/R)) \qquad (6).$$

Fig.10 shows light-current characteristic of a bonded 910μm - long diode. The laser was tested up to pulse power of 150mW and demonstrated η_d~18% per two facets, that is typical of these long-cavity diodes. Maximum value of η_d~25% was obtained for the diodes with L = 450-500μm. An inhomogeneous lasing intensity distribution across the stripe area (lasing in "filaments") may be one of the reasons for the low value of η_d for broad-area lasers [11]. However, in this case spontaneous emission intensity should be expected to increase above the threshold, while in our case it exhibits a rapid saturation with current, typical of high-quality MOCVD-grown AlGaAs/GaAs lasers. Taking into account this result as well as the above mentioned high efficiency of spontaneous emission, we have to explain the low differential efficiency by internal losses only. The main sources of internal losses in double heterostructures are light absorption by free carriers in the active region and cladding layers, optical scattering loss due to irregularities at the heterointerfaces and coupling loss when the optical field spreads beyond the cladding layers. The experimental data for the lasers with cavity lengths of 450-910μm can be explained with the assumption of internal losses α_i of about 40cm^{-1} which is higher than the known values for AlGaAs structures and cannot be ascribed solely to the free carrier absorption. Low value of Γ~0.3 and the deep penetration of the lasing mode to the cladding layers may be the reason for additional distributed losses, such as light scattering at heterointerfaces and coupling losses in the contact layer. We expect this source of losses to be eliminated with the transition to separate confinement heterostructure lasers having the lasing mode confined stronger to the waveguide region.

Separate-confinement heterostructure (SCH) laser, as proposed in 1973 by Thompson ano Kirkby, is basically a four- or five-layer dielectric waveguide where first composition step gives an energy band discontinuity necessary to confine injected carriers within the active layer, while second step in the refractive index between the waveguide and cladding layers provides light confinement within the optical cavity. Separate optical and electrical confinement ensures moderate beam divergence and low optical power density on the laser mirror while preserving fundamental transverse mode operation and low threshold current density for the lasers with thin active layers. Separate confinement is critical for modern quantum well lasers being the only structure design providing strong overlap of lasing mode with thin active layer. Also, since optical wave is propagating mostly through undoped waveguide layers rather than doped cladding layers, as in double heterostructure lasers, external efficiency may be made higher due to lower free carrier losses.

As has been mentioned earlier, decreasing cavity length from 910 to about 400μm leads to some increase in differential external efficiency. However, further decreasing the cavity length results in the rapid growth of the threshold current densities without any improvement of η_d. We consider the reason for this kind of anomalous behaviour of short diodes to be the relatively low confinement barrier height. Under this condition, the increase of excess carrier concentration in the active region can lead to a sharp increase in electron current leakage from the active region to the p-type cladding layer. As shown in [14], this leakage not only results in higher threshold current density, but also reduces the differential efficiency. The current leakage enhancement under current density increasing up to 2-3kA/cm^2 manifests itself by the corresponding enhancement of temperature dependence of spontaneous emission efficiency for short-cavity non-lasing diodes (a decrease of η_e is more than 50% for temperature increase from 300 to 380K at 3kA/cm^2). The effect of leakage should also be less pronounced in SCH-SQW lasers with lower threshold current densities of a few hundreds A/cm^2.

In conclusion, we report the following results obtained in our work:

1. InGaAsP/GaAs laser diodes emitting in the 0.8μm region were prepared by MOCVD for the first time. The investigation of the lasers fabricated showed that at the pumping current densities

below 1 kA/cm^2 almost all the injected carriers recombine radiatively in the quaternary 0.1 μm - thick InGaAsP active region ($\eta_i \sim 100\%$). This provides the threshold current densities for long-cavity double heterostructure laser diodes to be as low as 700 A/cm^2 which is better than the values for similar AlGaAs DH lasers and approaches the theoretical limit.

2. The results reported allow to suggest the fabrication of separate confinement heterostructure lasers based on the same MOCVD-grown high-quality InGaAsP material to eliminate the inherent drawbacks of DH lasers studied and to obtain laser diodes with the parameters superior than the best results for SCH SQW AlGaAs lasers.

References:

[1] M. Razeghi, F. Omnes, Ph. Maurel, Y. J. Chan and D. Pavlidis, Semicond, Sci. Technol. 6, 103 (1991).

[2] Y.J. Chan, D. Pavlidis, M. Razeghi, F. Omnes, IEEE J. Electron Devices 37, 2141 (1990).

[3] M. Razeghi, F. Omnes, M. Defour, Ph. Maurel, J. Hu, E. Wolk and D. Pavlidis, Semicond. Sci. Technol. 5, 278 (1990).

[4] M. Razeghi, F. Omnes, M. Defour, Ph. Maurel, Ph. Bone, Y. J. Chen, and D. Pavlidis, Semicon. Sci. Technol. 5, 274 (1990).

[5] K. Mobarhan, M. Razeghi, G. Marquebielle, and E. Vassilaki, J. Appl. Phys. 72, 9 (1992).

[6] K. Mobarhan, M. Razeghi, and R. Blondeau, Electronics Lett. 28, 16 (1992).

[7] D. Z. Garbuzov, N. Yu. Antonishkis, S. N. Zhigulin, N. D. Il'inskaya, A. V. Kochergin, D. A. Lifshitz, E. V. Rafailov, and M. V. Fuksman, Appl. Phys. Lett. 62,10 (1993).

[8] D. Z. Garbuzov, N. Yu. Antonishkis, A. D. Bondarev, A. B. Gulakov, S. N. Zhigulin, N. I. Katsavets, A. V. Kochergin, and E. V. Rafailov, IEEE J. Quantum Electron. 27, 6 (1991).

[9] X. He, E. Kolev, and M. Razeghi, to be published.

[10] Zh. I. Alferov, I. N. Arsent'ev, D. Z. Garbuzov, E. Tulashvili, Sov. Phys. Semicond. 25, 99 (1983).

[11] J. C. Dyment, F. R. Nash, C. J. Hwang, G. A. Rozgonyi, R. L. Hartman, H. M. Marcos, and S. E. Haszko, Appl. Phys. Lett. 24, 481 (1974).

[12] J. Thompson, "Physics of Semiconductor Laser Devices", John Wiley & Sons Ltd. (1980).

[13] S. Adachi, J. Appl. Phys. 53, 5863 (1982).

[14] D. Z. Garbuzov, V. B. Khalfin, In: "Quantum Well Lasers", ed. P. Zory, Academic Press (1993).

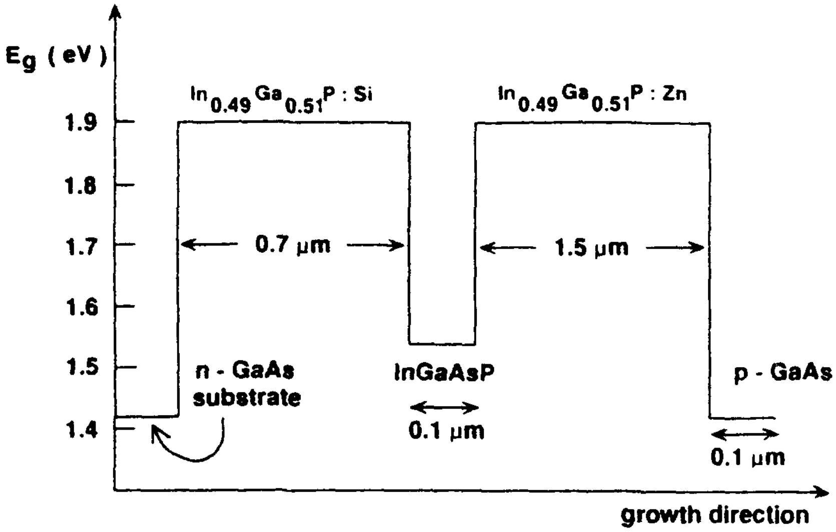

Fig.1 Schematic band diagram of the doubie heterostructure InGaAsP/InGaP/GaAs 0.8μm laser structure.

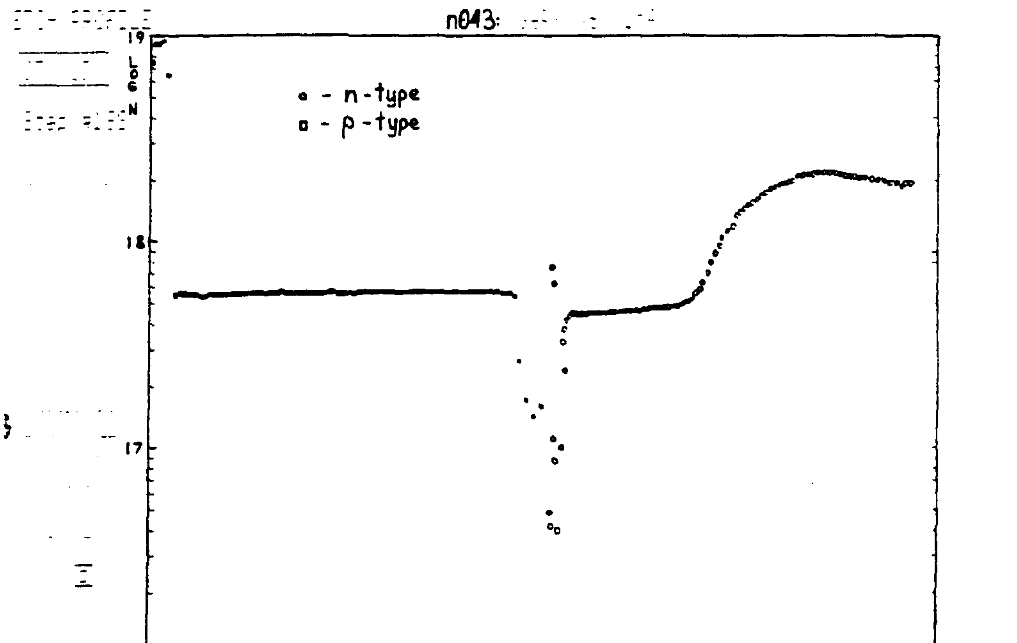

Fig.2 Electrochemical doping concentration profile of the laser structure #43.

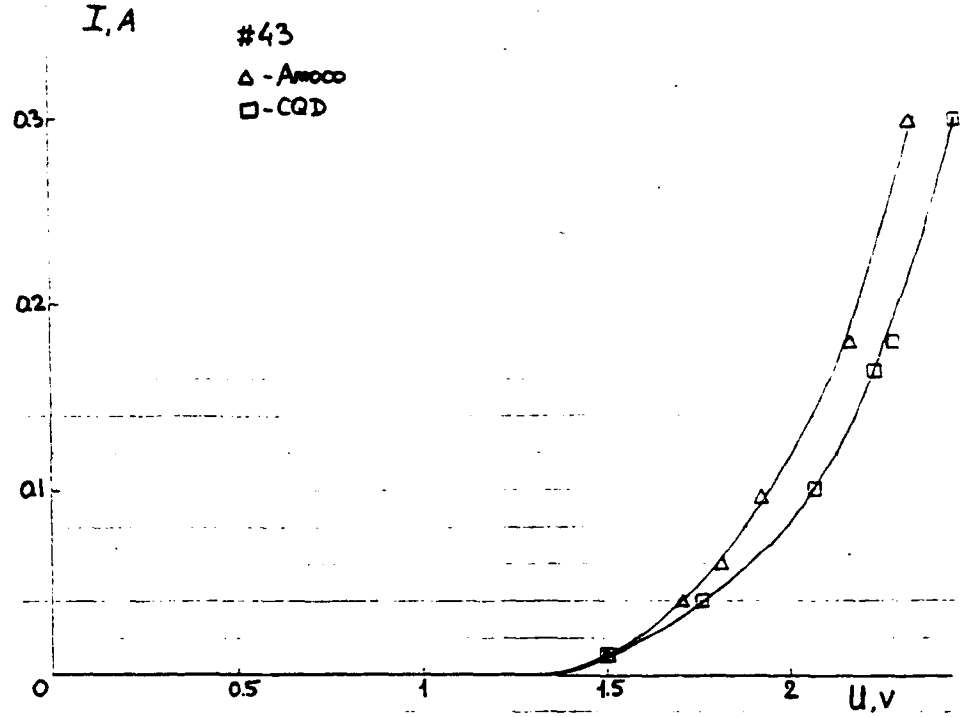

Fig.3 Typical current - voltage characteristics of two diodes of wafer #43 with the same stripe area prepared by Amoco Technology Co. and Center for Quantum Devices.

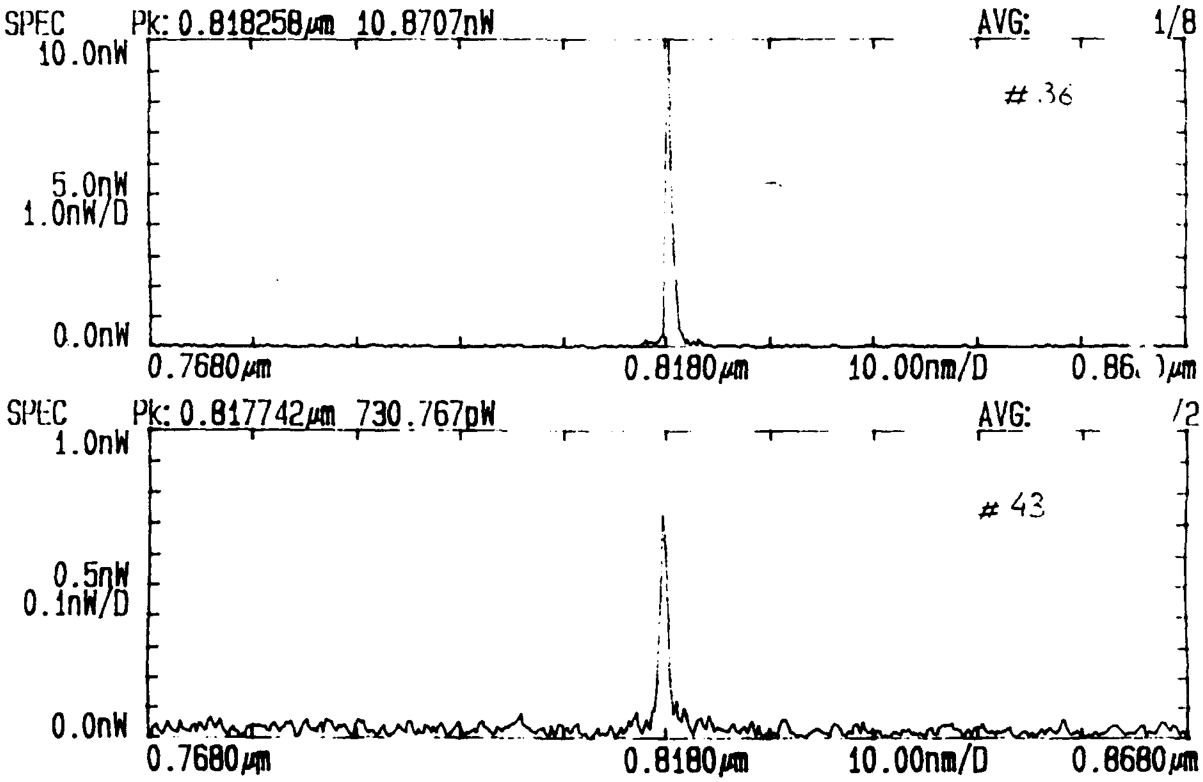

Fig.4 Lasing spectra of two diodes prepared from wafers #43 and #36.

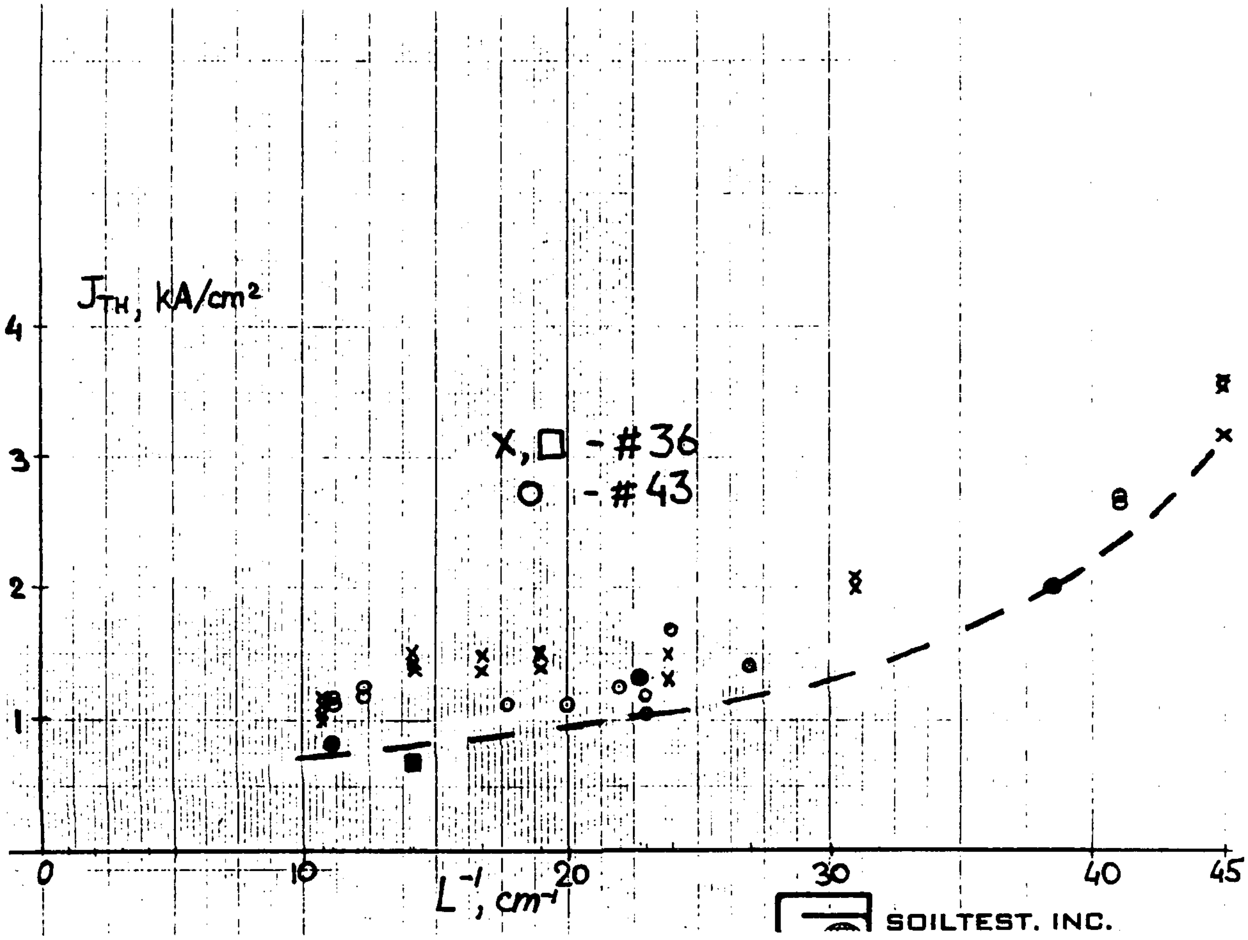

Fig.5 Threshold current density as function of reciprocal cavity length for 100μm stripe diodes of wafers #36 and #43. Filled notations correspond to bonded diodes.

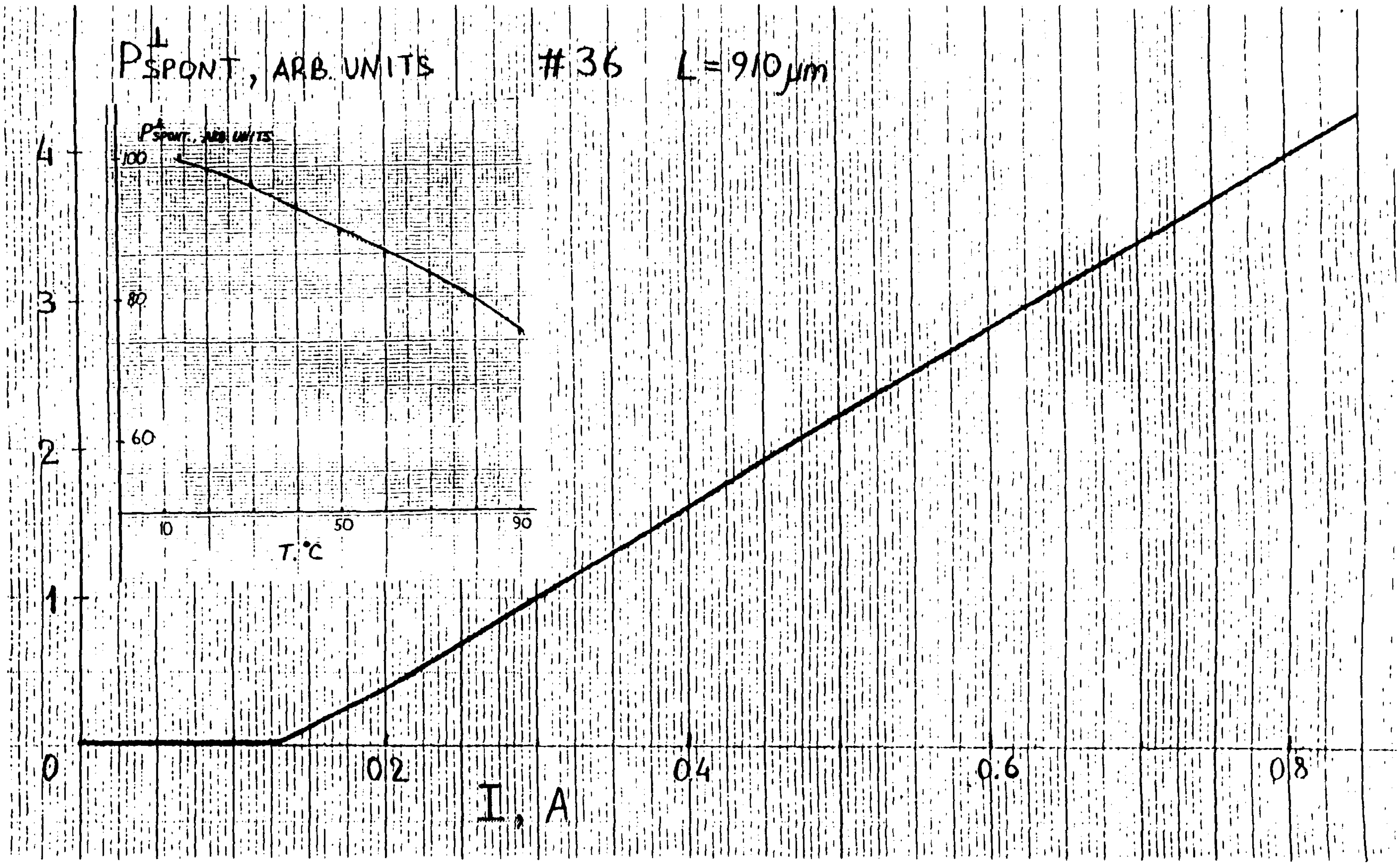

Fig.6 Spontaneous emission intensity vs current for diode of wafer #36 with 100ns driving pulse. Radiation coupled out in the direction normal to the p-n junction plane. Inset: Temperature dependence of spontaneous emission at pulse current density of $400A/cm^2$.

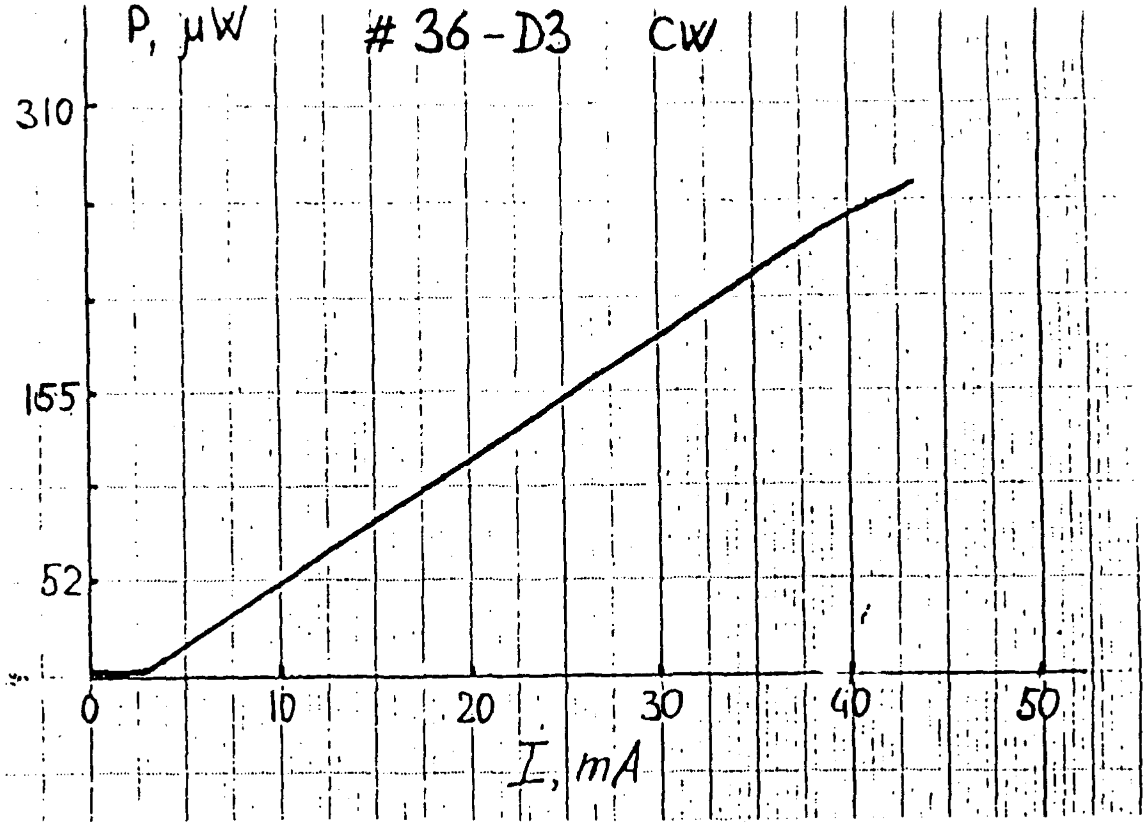

Fig.7 Spontaneous emission output through one of the mirrors for a diode with cavity length 110μ m.

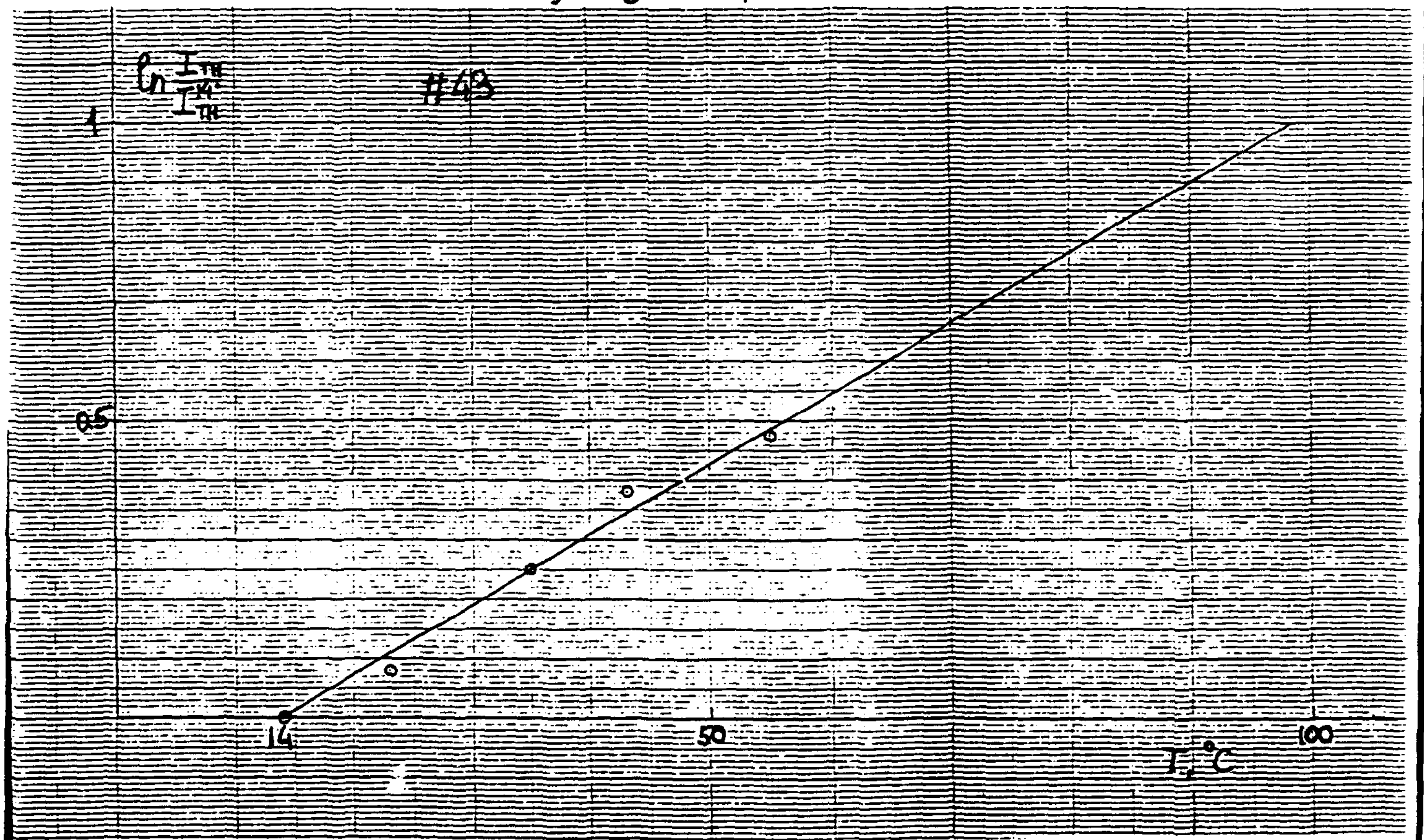

Fig.8 Temperature dependence of Jth for bonded laser diode of wafer #43 with cavity length 710μ m.

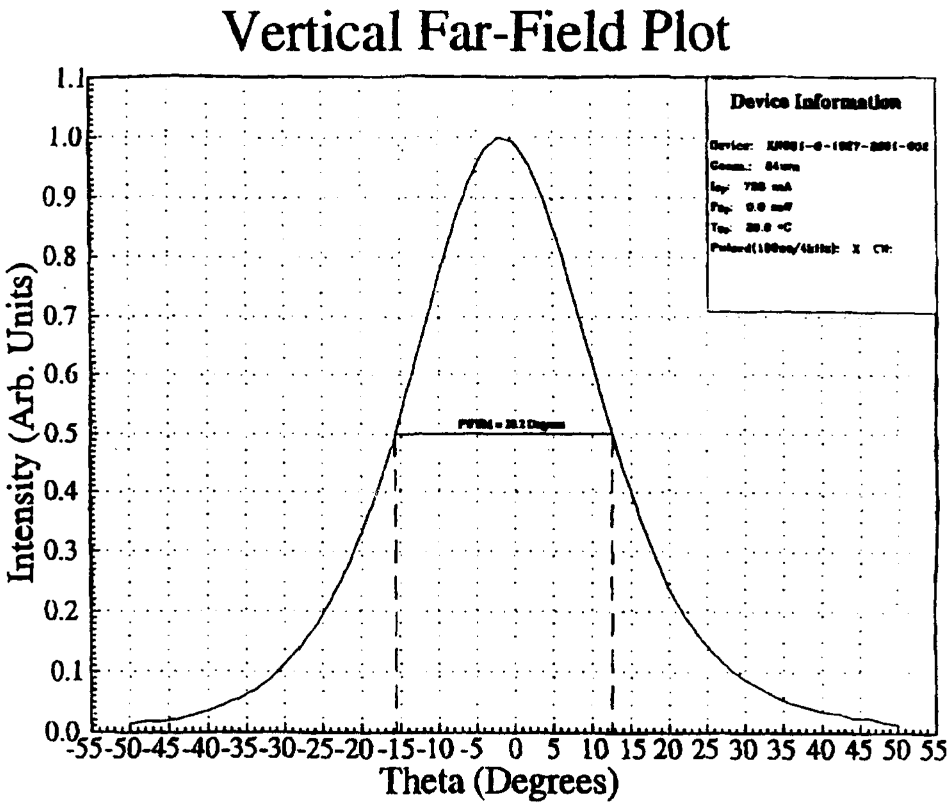

Fig.9 Far-field pattern in the direction perpendicular to the junction plane of 200μm - wide stripe bonded laser diode of wafer #43.

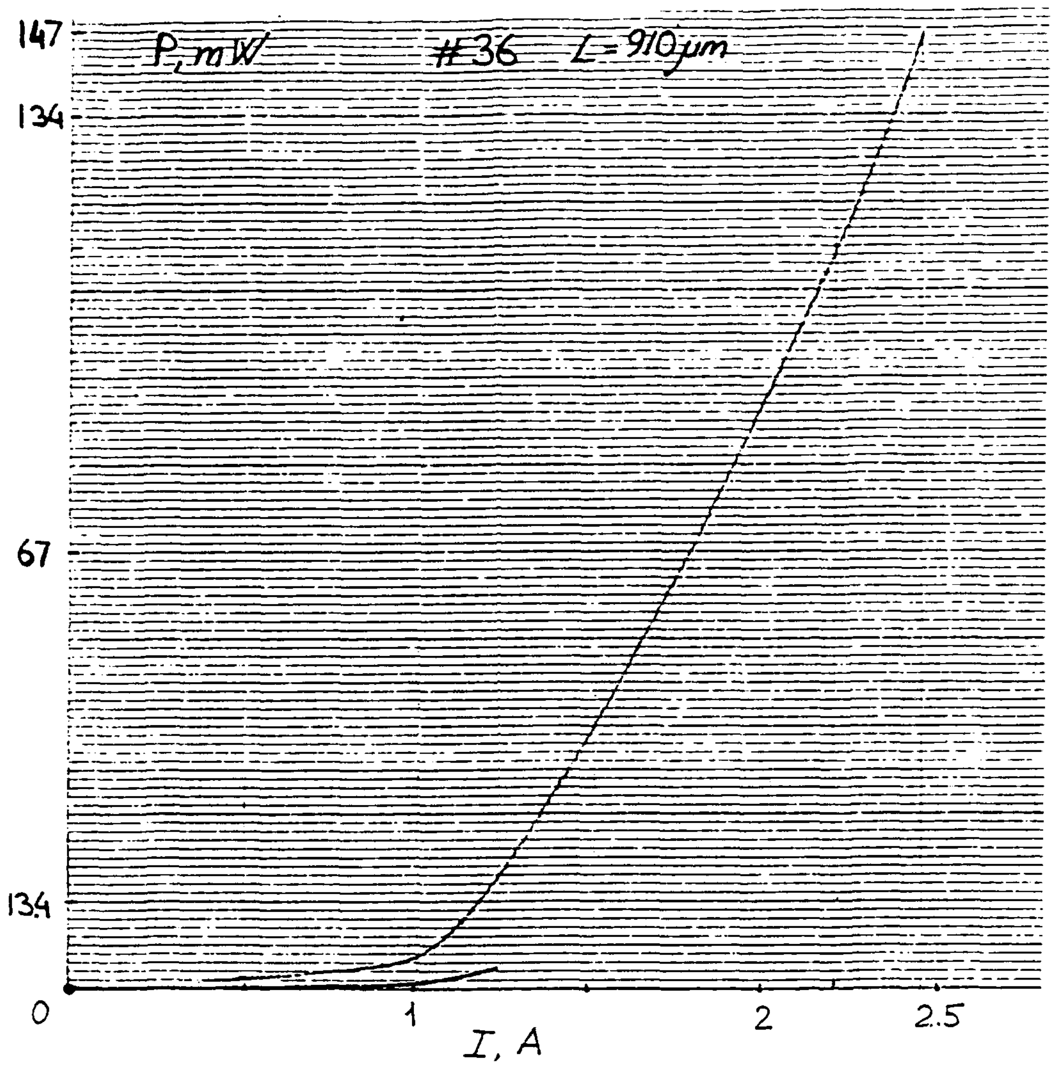

Fig.10 Light-current characteristic of a bonded diode of wafer #36 with cavity length 910μ m.